STEAM INJECTION PRESSING

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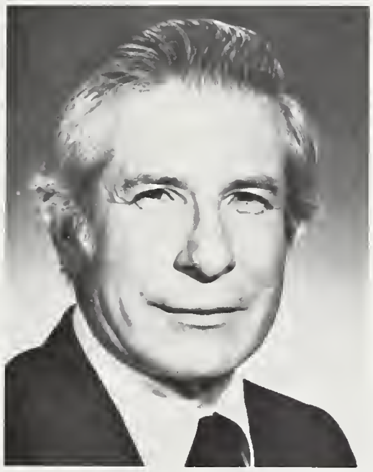

ABSTRACT

A process developed at the U.S. Forest Products Laboratory injects saturated steam into a flakeboard mat during press closure to reduce the time needed to bring the centerline of the flakeboard to resin curing temperatures. Total press time for a ½ in. (13 mm), 40 lb/ft^3 (641 kg/m^3), phenolic-bonded flakeboard has been reduced by 60%, without degrading internal bond or flexure properties. Control over plasticization of the mat reduces press closing pressures and provides a means to significantly alter the vertical density profile.

INTRODUCTION

A reduction of 1 second in the press cycle in a large (90 million ft^2/yr, ¾ in. basis) particleboard plant can potentially result in a $35,000 increase in annual sales. For this reason, production-minded particleboard manufacturers are constantly striving to shave precious seconds from press times. Innovations in machinery design, adhesive formulations, and pressing techniques have succeeded in reducing press times from 20 minutes [common 30 years ago for a ¾ in. thick (19 mm) board] to less than 5 minutes in modern-day plants.

One means of reducing the press cycle is to reduce the time necessary to bring the thermosetting resin in the center layer of the board to curing temperatures. The mechanism by which heat is transferred from the heated platens or caul plates, which contact the surface of the board, to the board's inner core has been described as an undulating steam front [1]. Moisture in the surface layers of the board is converted to steam and moves through the voids of the porous board by convection until the steam condenses.

A new steam front reheats the condensed moisture and penetrates further into the board. When this succession of vaporization and condensation waves reaches the center layer of the board, the core temperature rises to a plateau level determined by the rate of heat transfer and the loss of steam through the edges of the board. Only after most of the moisture has been driven from the core does the core temperature rise and begin to equal the surface temperature. To produce at a competitive capacity, today's flakeboard facilities depend upon the resin's curing at the plateau level temperature. The time it takes for the central layer to reach this temperature depends upon many factors, including particle type, board thickness, mat moisture, mat density, press temperature, and press closing rate. The time it takes for the temperature in the core of a 0.5 in. thick (13 mm) board to reach the plateau level may range from 45 to 90 seconds. This warm-up period is considerably extended in a nonlinear fashion as panel thickness increases, and it can be as long as 45 minutes for a 2 in. thick (51 mm) board [2].

Increasing platen temperature and rate of press closure shortens the warm-up period by increasing the rate of heat transfer [3]. Both of these variables, however, are limited by mechanical factors, and both must be optimized in regard to other desired board characteristics such as the extent of surface layer "precure" and the board's density profile.

Increasing mat moisture within certain limits will also improve the heat transfer rate. Changing this variable, however, may also influence other production operations such as resin blending, resin cure, and press decompression rate.

Proper manipulation of the distribution of moisture throughout the mat will further reduce heat transfer times. A most effective technique to enhance heat transfer by moisture distribution is known as "steam shock" [4], whereby water mist sprayed on the surface of the mat is converted to steam upon contact with the hot platen and rapidly penetrates the mat.

BACKGROUND

Various means to reduce press times by injecting steam into the board during some phase of the pressing cycle have been proposed or tried. Klauditz obtained a German patent in 1959 on a process using superheated steam injected into the mat after the press had closed to final board thickness [5]. The process is limited to low-density boards and thermosetting resins that cure below 212°F (100°C). The patent also described means of reducing residual moisture content. A U.S. patent issued in 1966 to Corbin and Hall, assignors to Weyerhaeuser Co., details the use of superheated steam injected into the mat during press closure through a single perforated platen [6]. The process substantially reduces both total press time and press closing pressure. Corbin believed that the use of saturated steam limited temperatures to 212°F (100°C) and substantially increased residual moisture content.

In 1968 Stegmann and May published details of an experiment involving the transmission of steam edgewise through the panel [7]. A German patent issued in 1972 to Voelskow *et al.* proposes a continuous press incorporating the injection of superheated steam into the mat to aid in reducing closing pressure [8]. After being compressed to the desired thickness, the board passes through hot and cold gassing zones that have been incorporated into the press. Another German patent issued in 1974 to Alenius describes a device whereby gases or liquids may be injected into the panel during the press cycle [9]. A French patent issued in the same year to Okhotskii *et al.* describes the use of superheated steam injected into the mat to produce a board with no binder [10]. The process used long periods (5 to 10 minutes) of steaming followed by periods of hot pressing.

Shen holds patent rights on a process he described in a 1973 publication [2, 11]. In this process, steam was introduced into the mat following closure to final thickness in a press that was edge-sealed. By controlling the exhaust of the steam through a series of valves, he was able to maintain relatively high pressures and temperatures, producing boards in a short period of time having exceptionally good dimensional stability. Thoman, experimenting with a sealed system, also reported improvements in panel dimensional stability but claimed that bending and internal bond (IB) properties were reduced

due to steam condensation, which prevented total resin cure [12].

All these processes showed that steam injection pressing increased the heat transfer rate, but the commercialization of these processes was hampered by the difficulties involved with sealing a large press and/or the additional expense of incorporating superheaters into the system. With the advent of "high cost" energy, however, the potentials of steam injection pressing have become more attractive. The following section describes a process developed at the U.S. Forest Products Laboratory utilizing saturated steam injected through both top and bottom surfaces during press closure. The mat itself acts as an outlet valve (Figure 1).

Exploratory Research

Steam injection pressing research, begun in 1973 at the Forest Products Laboratory, was motivated by an interest in curing 7 in. thick (178 mm) reconstituted products. It soon became apparent that the process could substantially reduce press times of thinner panels, and the work was redirected towards this goal.

A set of 36 by 36 in. (914 by 914 mm) perforated platens was built to fit the Laboratory press (Figure 2). The platens were perforated with 3/32 in. diameter (2.38 mm) holes drilled in a 0.5 by 2 in. (13 by 51 mm) spacing pattern which covered an area of 22 by 26 in. (559 by 660 mm). The perforated platens were attached to the normal oil-heated press platens, which in turn were kept at a temperature above 300°F (149°C). Steam at 98% quality and 210 lb/in.^{2} (1440 kPa) maximum line pressure was supplied from a common ½ in. diameter (13 mm) line through a set of separators to the manifolds of the perforated platens.

The raw material used in the majority of the exploratory work was 0.020 in. thick by random (R) width by 2 in. long (0.5 mm by R by 51 mm) Douglas-fir ring-cut flakes. A few boards were made using planer shavings, disk-cut flakes, wafers, and fibers.

This early exploratory work established the principles of steam injection pressing using saturated steam. Successful use of saturated

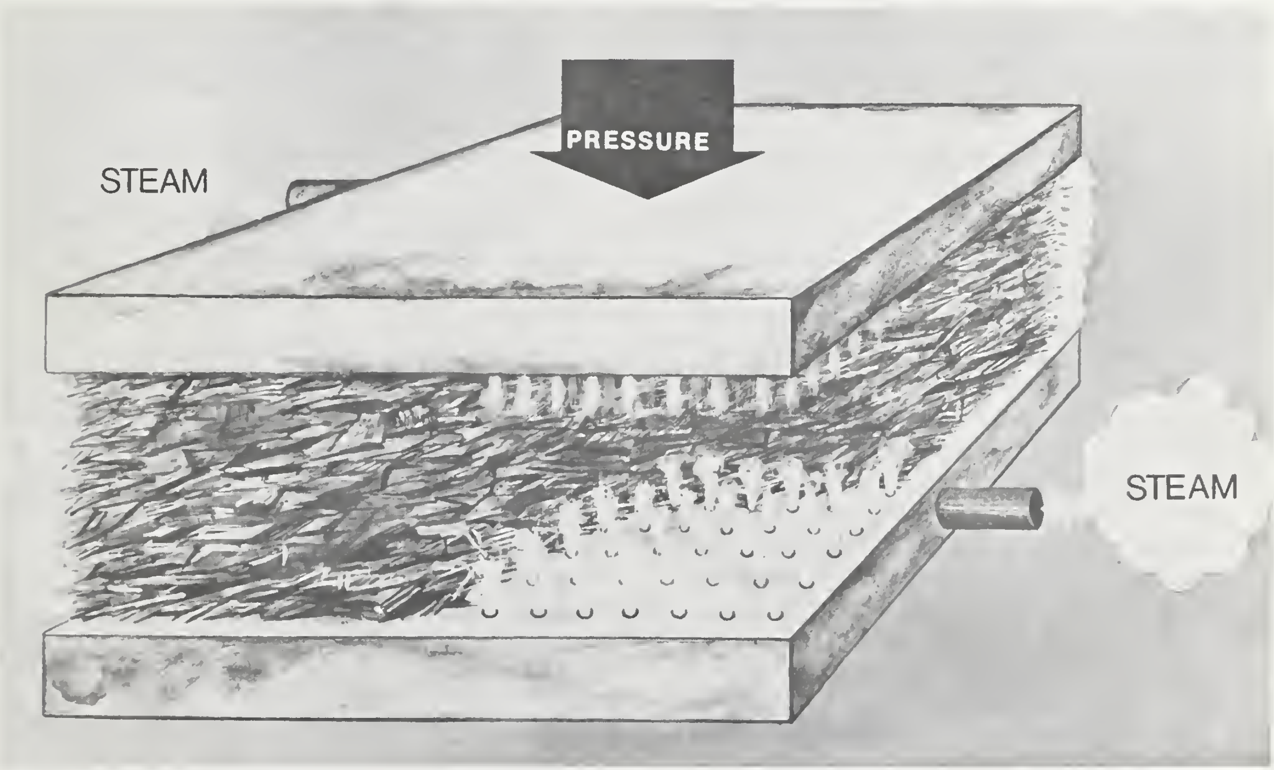

Figure 1. *Saturated steam is injected into the mat through top and bottom perforated platens during press closure.*

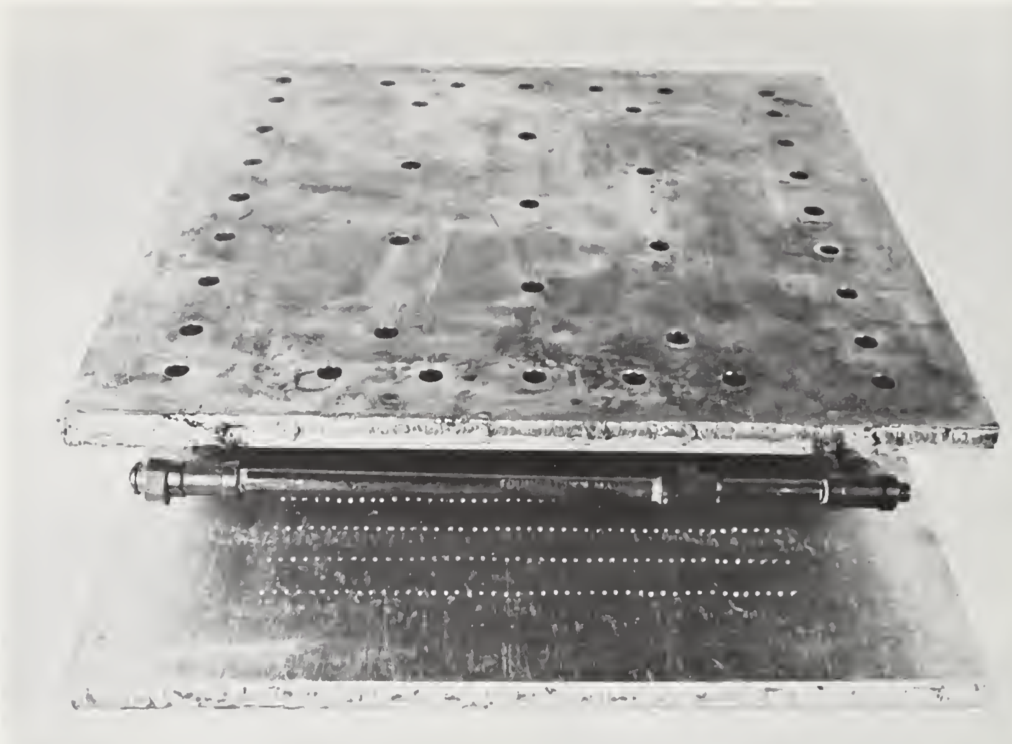

Figure 2. *Photograph of 36 by 36 in. (914 by 914 mm) perforated platens used for steam injection. 3/32 in. diameter (2.38 mm) holes are drilled in a 0.5 by 2 in. (12.7 by 50.8 mm) spacing pattern, covering a 22 by 26 in. (56 by 66 mm) area.*

steam to reduce heat transfer time depended on close control of certain variables having narrow limits:

> Steam must be introduced before the mat is compressed to a critical density level. This density is 27 lb/ft^3 (433 kg/m^3) and varies slightly with the furnish type. At mat densities below 27 lb/ft^3 (433 kg/m^3), the steam penetrates between particles or flakes and creates permanent paths to the center and edges of the board.
>
> The center of the board must reach a temperature of 212°F (100 °C) prior to the mat's being compressed to a density of approximately 35 lb/ft^3 (561 kg/m^3). Otherwise, excessive steam condensation occurs and maximum centerline temperatures cannot be reached.
>
> Steaming for a short period after the board has been pressed to its final thickness allows the centerline temperature to reach a peak value, which is determined in most part by the density of the mat and the amount of steam flow.
>
> When steaming is terminated, the centerline temperature decreases rapidly to some value, approximately 225°F (107°C) in a 40 lb/ft^3 (641 kg/m^3) board, and remains at this level throughout the curing stage. The additional time required to achieve adequate cure depends on the resin characteristics and may be as long as 80 seconds for a phenolic-type resin or as short as 13 seconds for some of the faster curing ureas.

Typical thickness-core temperature-board pressure/time curves for both a conventionally pressed board and a steam-injected board are shown in Figures 3 and 4. These minimum press-time curves were developed from boards that were pressed using a phenol-formaldehyde resin. Platen temperature in both cases was 375°F (190°C). Core temperature in the conventionally pressed board rose to a plateau level of 250°F (121°C) in approximately 2 minutes. The remainder of the time, 90 seconds, was required to cure the phenolic resin. This cure time was practically identical to the total press time needed for a steam-injected board. Steam injection essentially eliminates the initial warm-up period.

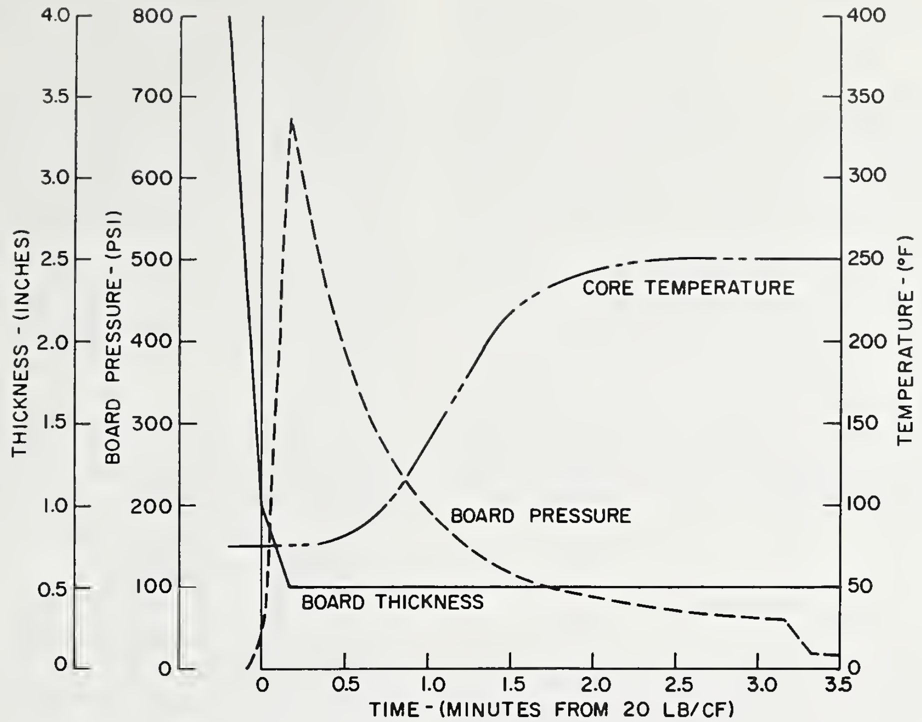

Figure 3. *Press curves for a conventional hot-pressed flakeboard (similar to type 27). 375°F platen temperature.*

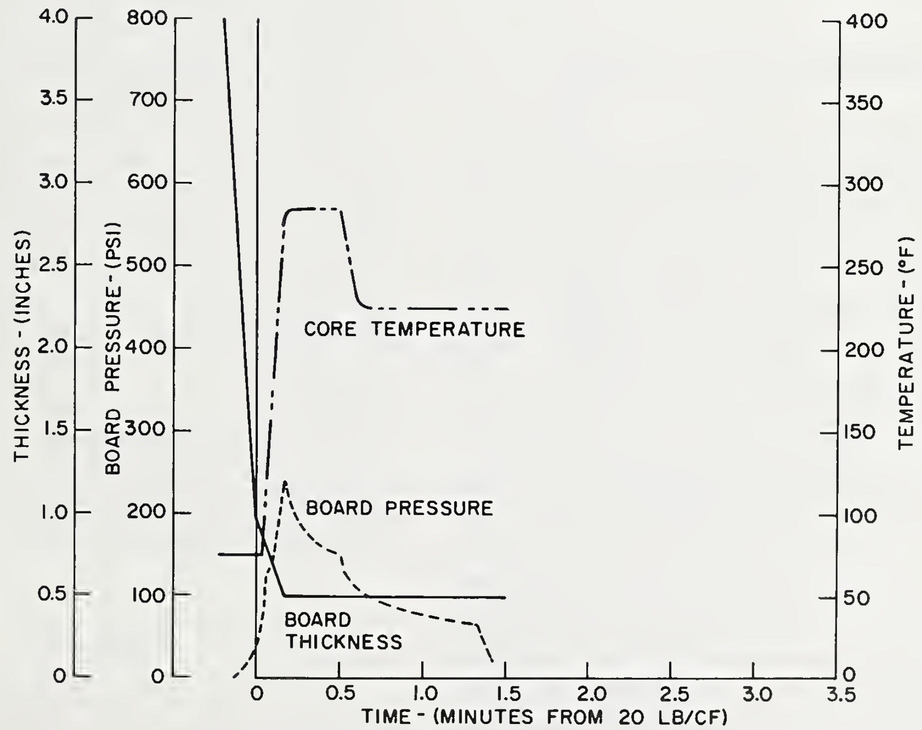

Figure 4. *Press curves for a steam-injected flakeboard (similar to type 20).*

Because the conditions for successful steaming were found to be so narrow and because they occurred in such a short period of time, improvements in press controls were necessary prior to beginning any controlled experiment at the Laboratory. Manually operated press controls were replaced with fully automated programmable equipment [13]. The new system provided press closure tolerances of ± 0.003 in. (0.0076 mm), pressure tolerances of ± 5 lb/in.^{2} (34.5 kPa), and programmed time function accuracy of less than 1.5 seconds within the ranges encountered in steam pressing. The system, which also included solenoid-operated steam valves, permitted further exploration of steam injection pressing.

OBJECTIVE

The objective of this study was to determine how the variables of steam injection pressing (steam duration, pressing time, and press closure rate) influence mat temperature, pressure, and moisture content, and board physical properties and density profiles.

EXPERIMENTAL DESIGN

All boards in this experiment were homogeneous in nature and fabricated with 0.020 in. thick by random width (R) by 2 in. long (0.5 mm by R by 51 mm) Douglas-fir ring-cut flakes bonded with 5% liquid phenolic resin. Two replications were made of all board types. With two exceptions, all boards were ½ in. (13 mm) thick and had a density of 40 lb/ft^3 (641 kg/m^3). A ½ in. (13 mm) thick, 50 lb/ft^3 (801 kg/m^3) board and a ¾ in. (19 mm) thick, 40 lb/ft^3 (641 kg/m^3) board were included in one portion of the experiment. All boards were 24 in. (609 mm) wide and 28 in. (711 mm) long. This left a 1 in. (25 mm) wide margin beyond the outside edge of the holes in the perforated platens to act as a steam seal. The regular oil-heated platens were held at a constant temperature of 375°F (190°C). Steam used for injection was 98% quality at a maximum line pressure of 210 lb/in.^{2} (1440 kPa). No attempt was made in this study or in previous exploratory work to monitor steam flow rates. Later instrumentation indicated maximum steam flow to be approximately 850 lb/hr (385 kg/hr).

The basic experimental design is outlined in Table 1. In the first group, steam was injected into all boards at a mat density of 20 lb/ft^3 (320 kg/m^3). Press closing rates and steam duration were varied. The boards were held in the press for 4 minutes, enough time for full resin cure, which allowed the evaluation of the effects of steam duration and closing rates on the mechanical properties and density profiles of the boards.

In the second group, steam injection was delayed until the mat had reached a density of 25 lb/ft^3 (401 kg/m^3). Closing rate and steam duration were again varied, but press time was maintained at 4 minutes.

The boards in the third group were all pressed using a fast closure rate of 15 in. per minute, with a total press time of 2 minutes. The beginning point of steam injection and the duration of steaming were varied.

The fourth group contained the two board types that varied in density and thickness. These were pressed for a total of 4 minutes. The board density at the time of initial steam injection was 25 lb/ft^3 (401 kg/m^3), and total steam time varied only slightly between the two board types.

A final set of steam-injected boards was made to determine the minimum press times obtainable with a ½ in. (12 mm) thick, 40 lb/ft^3 (641 kg/m^3) board using a phenolic resin. Press closure rates and steaming durations were selected to provide what was thought to be optimum conditions and, except for board No. 20, varied only slightly among the boards in this group.

The sixth group was control boards pressed in the conventional manner with a platen temperature of 375°F (190°C). Variations within this group included press time, closing rate, board thickness, and board density.

TESTING

Sample cut-up is shown in Figure 5. Density gradients were obtained using a planer to successively remove 0.030 in. (0.762 mm) layers. Bending strength (MOR), bending stiffness (MOE),

Table 1. Pressing conditions.

Board type No.	Press time[1/]	Injection SG[2/]	Close rate[3/]	Steam time[4/] Before	Steam time[4/] After	Maximum pressure[5/]	30-second pressure[6/]	Maximum temperature	MC from press[7/]
	sec		in./min	sec	sec	$lb/in.^2$	$lb/in.^2$	°F	%
GROUP 1--4-MINUTE PRESS TIME, STEAM INJECTED AT 0.320 SG									
0	240	0.320	6	5	5	261	102	266	3.6
1	240	0.320	6	5	10	266	87	284	3.9
2	240	0.320	3	10	5	274	137	255	4.0
3	240	0.320	3	10	10	281	132	245	4.5
19	240	0.320	[8/] 3	10	10	202	77	289	4.1
4	240	0.320	1.5	20	5	255	115	277	4.4
Average	--					256	108	270	4.1
GROUP 2--4-MINUTE PRESS TIME, STEAM INJECTED AT 0.401 SG									
5	240	0.401	6	3	5	428	165	258	3.7
6	240	0.401	6	3	20	392	90	266	4.0
7	240	0.401	3	6	5	291	135	274	4.6
8	240	0.401	3	6	10	328	102	297	3.9
9	240	0.401	3	6	20	273	65	293	4.4
10	240	0.401	1.5	12	5	206	100	289	4.6
11	240	0.401	1.5	12	15	200	70	303	4.0
Average	--					302	103	282	4.2

Table 1. Pressing conditions--con.

Board type No.	Press time[1/]	Injection SG[2/]	Close rate[3/]	Steam time[4/] Before	Steam time[4/] After	Maximum pressure[5/]	30-second pressure[6/]	Maximum temperature	MC from press[7/]
	sec		in./min	sec	sec	$lb/in.^2$	$lb/in.^2$	°F	%
GROUP 3--2-MINUTE PRESS TIME, CLOSING RATE 15 in./min									
14	120	0.320	15	2	5	334	150	207	6.3
15	120	0.320	15	2	20	316	78	291	7.0
16	120	0.320	15	2	40	313	50	299	7.0
17	120	0.426	15	1	20	387	92	278	5.9
18	[9/]122	0.211	15	4	20	225	60	294	7.0
Average	--					315	86	286	6.6
GROUP 4--BOARD DENSITY AND THICKNESS VARIATIONS									
12 ($50\ lb/ft^3$)	240	0.401	3	10	10	432	220	294	4.2
13 (0.75 in.)	240	0.401	3	9	10	266	78	282	6.5
GROUP 5--MINIMUM PRESS TIMES									
20	90	0.356	3	8	20	206	75	225	7.8
21	90	0.320	7	4	20	240	68	287	9.0
22	60	0.320	7	4	20	239	75	279	8.5
23	38	0.320	7	4	18	245	95	292	10.3
25	33	0.320	7	4	25	225	130	275	9.8

Table 1. Pressing conditions--con.

Board type No.	Press time1/	Injection SG2/	Close rate3/	Steam time4/ Before	Steam time4/ After	Maximum pressure5/	30-second pressure6/	Maximum temperature	MC from press7/
	sec		lb/min	sec	sec	$lb/in.^2$	$lb/in.^2$	°F	%
GROUP 6--CONTROLS (NO STEAM INJECTION)									
31	240	--	6	--	--	665	320	250	2.0
26	600	--	6	--	--	712	322	308	0.1
27	240	--	3	--	--	632	290	245	3.1
28	600	--	3	--	--	690	300	304	0.1
68	180	--	3	--	--	--	--	--	--
Average	--					675	308	276	1.3
29 (50 lb/ft^3)	600	--	3	--	--	1,000	582	311	--
30 (0.75 in.)	600	--	3	--	--	765	335	242	2.5

1/ Press time begins at time mat reaches 20 lb/ft^3 (0.320 SG) or when steam is injected, if sooner.
2/ Specific gravity of mat at time of steam injection.

3/ Closing rate from 20 lb/ft^3 mat density (0.320 SG), initial rate of closure was 15 in./min.
4/ Steam time before and after press reached final board thickness.
5/ Board pressure at time press reached final board thickness.
6/ Board pressure 30 seconds after press reached final board thickness.
7/ Based on mat specifications and weight of board immediately after pressing.

8/ Press closed at 3 in./min from mat density of 16 lb/ft^3 (0.256 SG).
9/ Total press time includes 2 seconds of steaming prior to reaching mat density of 20 lb/ft^3 (0.320 SG).

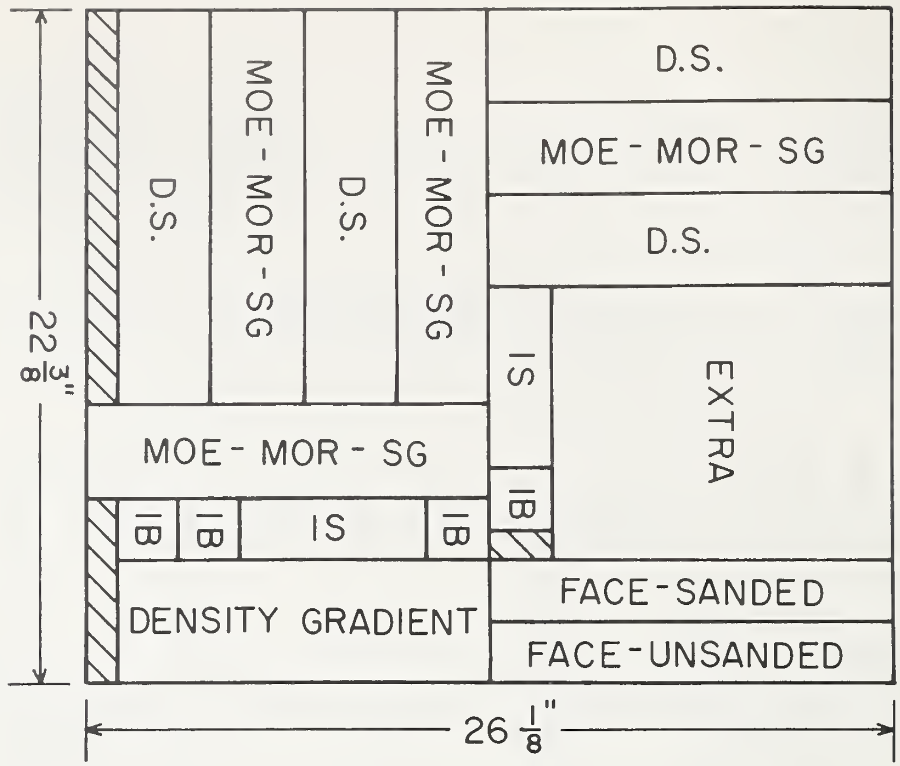

Figure 5. *Cutting diagram for steam-injected and control boards. DS = dimensional stability, 3 by 13 in.; IB = internal bond, 2 by 2 in.; FACE = face tension parallel, 2 by 13 in.; IS = interlaminar shear, 2 by 6 in.; MOE = modulus of elasticity; MOR = modulus of rupture; SG = specific gravity, 3 by 13 in.; density gradient, 4 by 12 in.*

internal bond (IB) and interlaminar shear (IS) properties were tested according to ASTM D-1037 specifications following sanding to a thickness of 7/16 in. (11 mm) [14]. Face integrity was tested in tension perpendicular to the face using the jig shown in Figure 6. This test is used by industrial quality control personnel to determine the integrity of the glue bond between the layers of three-layer boards. Face strengths were measured on unsanded top and bottom surfaces and sanded top surfaces. The dimensional stability properties of thickness swell (TS) and linear expansion (LE) were determined on specimens following each exposure to a succession of oven-dry, 30% relative humidity (RH), 90% RH, vacuum-pressure-soak (VPS), and final oven-dry conditions.

DISCUSSION AND RESULTS

Temperature

The temperature rise in the core of the board is very sudden following steam injection. Depending on the type of furnish, mat density, and thickness, temperatures of 220°F (100°C) will be attained within 0.1 to 3 seconds. Core temperatures rise above 220°F (100°C) only after the board has reached the density level of 25 lb/ft^3 (401 kg/m^3). At this point the mat is dense enough to slightly retard steam flow. Pressure builds up in the platen manifold, and as densification continues, core-line temperatures increase. The temperature rise in the core of a steamed board that was made using a very slow closure rate is shown in Figure 7.

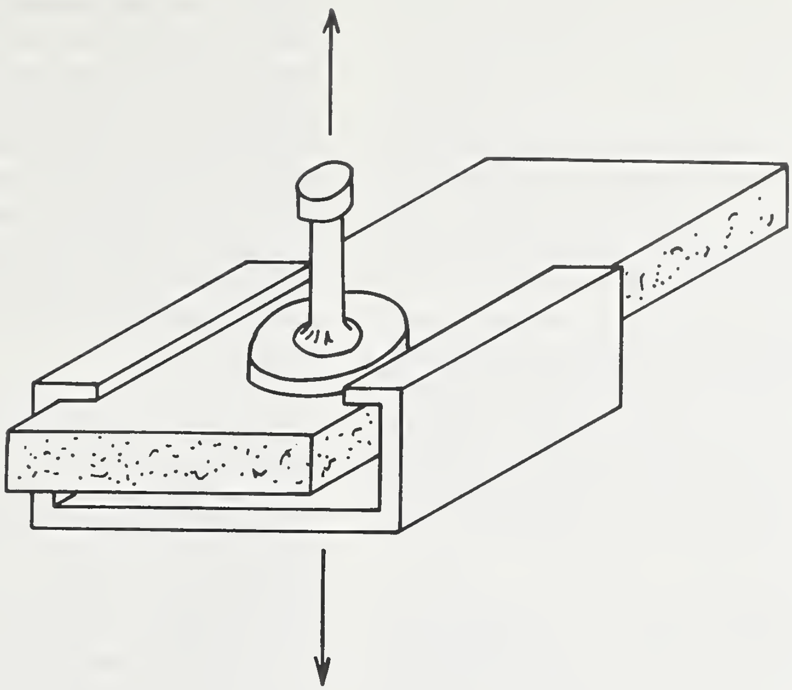

Figure 6. *Face strength evaluation. Area of tabs glued to the face of the board is 1 in.²*.

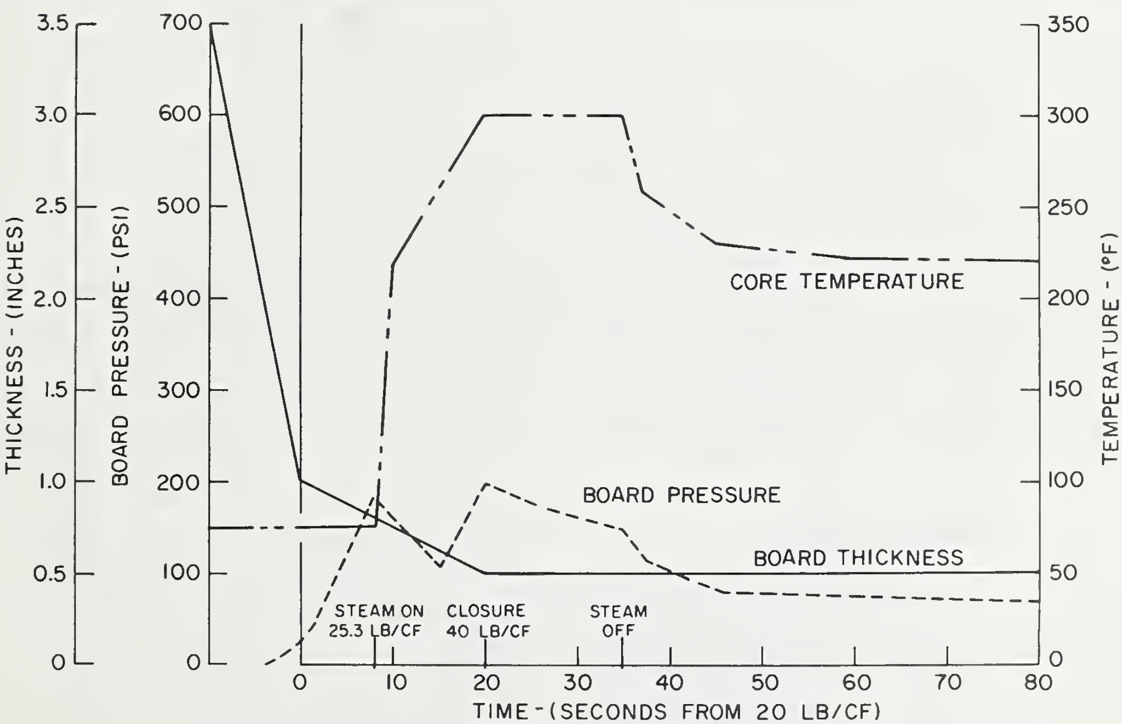

Figure 7. *Core temperature during steam injection is a function of mat density. Board pressure is a function of wood plasticization. Press curves are for a 40 lb/ft³, 0.5 in. thick board. Press closure rate is 1.5 in./min (similar to board type 11).*

Maximum core temperature attained in the boards under study was generally in the vicinity of 270°F (132°C). In some cases, temperatures as high as 303°F (150°C) were recorded (board No. 10). The cause of the variations in maximum core temperature could not be determined. It is possible that 0.5- to 1.5-second errors in the ability of the press to follow the programmed time/distance functions were sufficient to alter the temperature curves.

Maximum possible core temperatures were never fully attained in some of the boards that were exposed to a minimum duration of steam following press closure. The condition was most apparent when steaming times before and after closure were short and when the boards were made using a fast press-closure rate (board No. 14).

When steaming is stopped, core temperatures drop in a few seconds to a plateau level which is determined by the rate of heat transfer and the porosity of the mat. The permanent paths created by the injected steam increase mat porosity. Plateau temperature levels of 225°F (107°C) characteristic of a steam-injected 40 lb/ft^3 (641 kg/m^3), ½ in. (13 mm) thick board are 25° to 30°F (14° to 17°C) lower than those attained in a conventional hot-pressed board. A further indication of the creation of permanent steam passages can be seen in the rapid cycling of temperatures between plateau level and maximum when the steam is repeatedly turned off and on after the board has reached final thickness (Figure 8). This rapid cycling of temperatures is impossible to achieve in a board where steam injection has been delayed past the critical density level (27 lb/ft^3).

Pressure

Press closure is often defined as the time it takes to close to final thickness after both platens are in contact with the mat. In this study, press closure is defined as the time it takes to close the press to final thickness from a position at which the mat density is 20 lb/ft^3 (320 kg/m^3). Since very little board pressure [usually less than 10 lb/in.^{2} (69 kPa)] is needed to close the mat to 20 lb/ft^3 (320 kg/m^3), the rate of closure to this point depends only on the

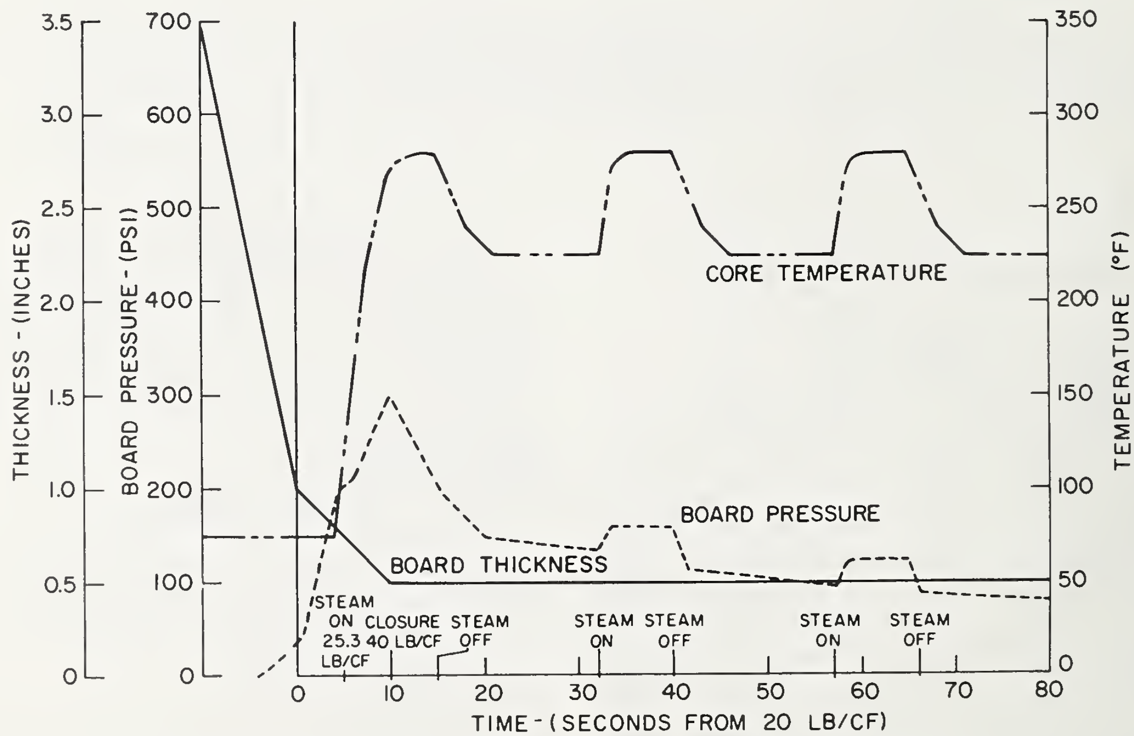

Figure 8. *If initial steaming procedures are correct, maximum core temperature is recovered immediately upon reintroduction of steam. Press curves are for a 40 lb/ft^3, 0.5 in. thick board. Press closure rate is 3 in./min (initial steaming similar to board type 7).*

volume capacity of the pump and is inconsequential when press accumulators are used or continuous pressing is considered. Unless otherwise stated, the press was programmed to close to a density of 20 lb/ft^3 (320 kg/m^3) at a rate of 15 in. (381 mm) per minute. At this speed it requires 14 seconds to reduce a typical uncompressed 4.5 in. (102 mm) thick mat to 1 in. (25 mm) in thickness [corresponding to 20 lb/ft^3 (320 kg/m^3)] mat density for a specified 40 lb/ft^3 (640 kg/m^3), ½ in. (13 mm) thick board].

The time to close from a mat density of 20 lb/ft^3 (320 kg/m^3) to final board specifications is relatively short. Many of the characteristics of the board, including its density profile, are established during this time. At a closure rate of 1.5 in. (38 mm) per minute, this critical period lasts 20 seconds for a specified 40 lb/ft^3 (641 g/m^3), ½ in. (13 mm) thick board. At a closure rate of 15 in. (381 mm) per minute, the last ½ in. (13 mm) of press travel requires only 2 seconds.

Board pressures required to reduce a control board (no steam injection) to final thickness at a closure rate of 3 in. (76 mm) per minute averaged 661 $lb/in.^2$ (4560 kPa). At the same closure rate, only 265 $lb/in.^2$ (1830 kPa) were needed to press a steam-injected board (Table 1). Under these conditions, steam-injected boards require only 40% of the closing pressure needed to press a board in the conventional manner.

The length of steaming time prior to closure affects closing pressure. The rate at which the steam plasticizes the mat can be observed in the pressure-distance-temperature/time curve representative of a board pressed at a slow closing speed (Figure 7). Pressure rises to 175 $lb/in.^2$ (1206 kPa) as the mat is compressed from 20 to 26 lb/ft^3 (320 to 416 kg/m^3). Upon introduction of steam, the pressure drops and continues to decline to 125 $lb/in.^2$ (862 kPa), at which time the mat has reached a density level of 35 lb/ft^3 (560 kg/m^3). As the mat is compressed further, pressure again rises to a maximum of 200 $lb/in.^2$ (1380 kPa). Exploratory trials have indicated that with the same preclosure steam time, plasticization is more complete in particles of smaller dimensions. Although more time is needed to raise the temperature of a fibrous mat, the closing pressure needed to compress a 40 lb/ft^3 (641 kg/m^3) fiberboard is reduced to less than 100 $lb/in.^2$ (690 kPa).

Closing pressures were dependent on closing speeds. The 220 $lb/in.^2$ (1520 kPa) pressure needed to close the press at a rate of 1.5 in. (38 mm) per minute was increased to 315 $lb/in.^2$ (2170 kPa) when closing rates were increased to 15 in. (381 mm) per minute.

At closing rates of 3 in. (76 mm) per minute, a 71% increase in pressure was required when board density was increased from 40 to 50 lb/ft^3 (641 to 801 kg/m^3). No additional pressure was required when final board thickness was increased to ¾ in. (19 mm).

Similar to conventional pressing, pressure falls off rapidly after final thickness has been reached. Thirty seconds following closure, the pressure required to hold position varies between 50 and 150 $lb/in.^2$ (345 to 1034 kPa). Note in the press curves (Figures 7 and 8) the additional pressure needed to overcome the steam injection force.

Moisture Content

Mat moisture content prior to pressing was targeted at 8% (oven-dry basis). The average moisture in the conventionally pressed control boards as determined by board weight from the press was 2% to 3% after 4 minutes of pressing. Moisture content of the steam-injected boards averaged 3.5% to 4.5% after 4 minutes of pressing. Average moisture content of those steam-injected boards that were pressed for 2 minutes was 6% to 7%. Only in those boards whose press times were 90 seconds or shorter did moisture content increase above the initial value.

Density Gradient

The density profile in a steam-pressed board tends to be very flat because of the uniform plasticization of the entire mat prior to closing. Density gradients characteristic of control boards are compared to those of steam-pressed boards in Figure 9. Manipulating closing rates and steaming periods before and after closure can considerably control the density profile. The density profile is extremely sensitive to steaming prior to

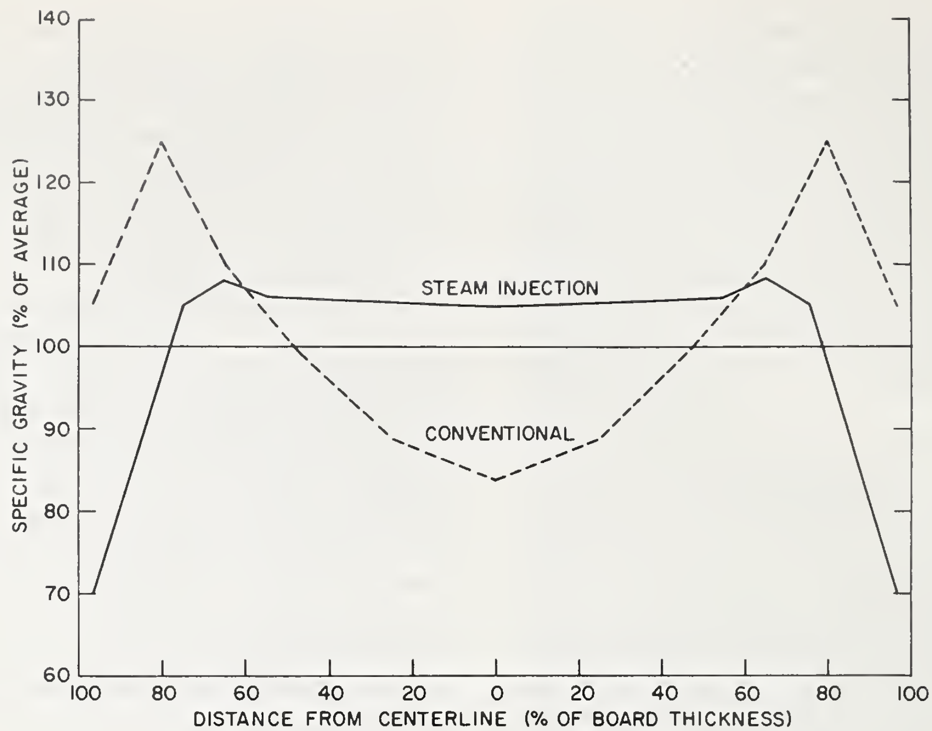

Figure 9. *Density gradients common to conventional (type 27) and steam-injected (type 7) flakeboard. Closing rate is 3 in./min for both boards. Steam injected for 6 seconds prior to and 5 seconds after press closure.*

press closure. In boards made with a fast press-closure rate, the profile is considerably flattened by increasing the presteam period from 1 to 4 seconds (Figure 10).

When preclosure steam times are short and particle plasticization is not complete, prolonged steaming following closure will further plasticize the mat, causing a shift in the density gradient. Response is slow, however, and up to 40 seconds of post-closure steaming are required (Figure 11).

For convenience sake all the boards made in this study were introduced into the press on a Fourdrinier screen. No screen was used on the top surface. Density profiles of those boards made with short durations of steam prior to closure and a fast closure rate tended to be unbalanced. The bottom faces had a higher specific gravity than the top. Similar to conventionally pressed boards, the density gradient of steam-injected boards is slightly increased as average board density increases and becomes noticeably steeper as board thickness increases (Figure 12).

In general, the low-density faces characteristic of the steam-injected boards can be entirely removed by sanding 0.050 in. (1.3 mm) from each side of the board. This is approximately the same amount of low-density face material that occurs in a conventionally pressed board. However, with the exception of those boards made with a very short steam time, the surface layers of a steam-injected board are much lower in density than the surface layers of conventional boards (Figure 9).

Properties

Physical properties of all board types are shown in Table 2. The experiment was designed to compare a large number of variables using a minimum of replications. Consequently, statistical analysis was difficult. A Duncan's multiple range test for variable response showed that after elimination of the more obvious differences, such as board types 12, 14, and 29, and the minimum press-time boards, IB differences between board types including the controls were

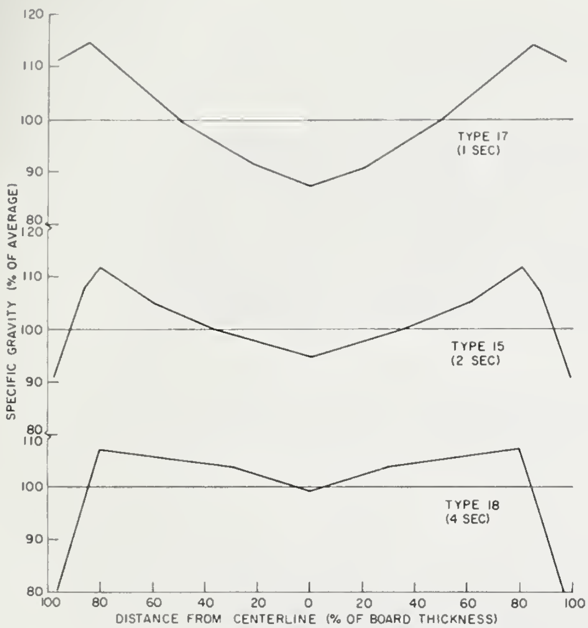

Figure 10. *Density profile is dependent on duration of steaming prior to press closure. Closure rate was 15 in./min, and steam time after press closure was 20 seconds. Number shown below board type is duration of steaming (seconds) prior to closure.*

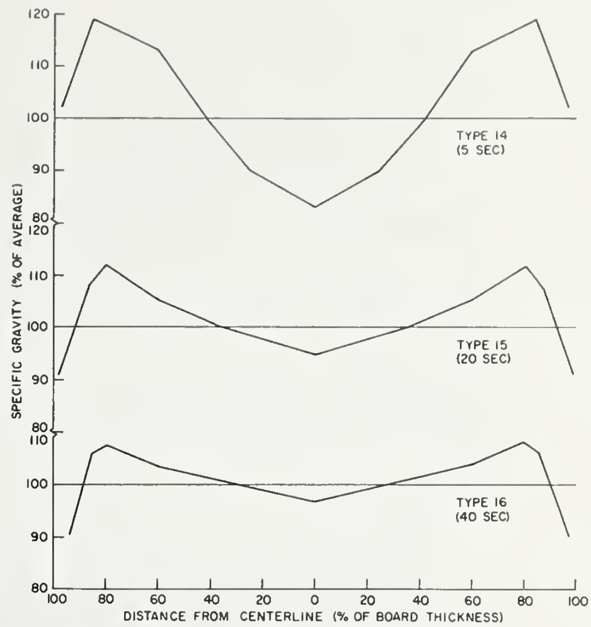

Figure 11. *Density profile is dependent on duration of steaming following press closure. Closure rate was 15 in./min, and steam time prior to closure was 2 seconds. Number shown below board type is duration of steaming (seconds) following closure.*

not large and could be explained with a 95% chance of being due to random errors.

Interlaminar shear (IS) followed much the same pattern. Bond strength might be reduced due to the dilution of the glue line by the injected steam; however, any deleterious effect on IB or IS properties caused by steam injection was compensated for by higher core densities. It is also probable that increased plasticization reduced flake damage and improved flake contact.

Bending properties were measured after sanding to 7/16 in. (11 mm) thickness. This left a residual density gradient in both the control and the steam-pressed boards that theoretically would result in optimum bending properties. Since bending properties are to a large extent determined by the properties of the outer layers, it was expected that the control boards that had higher density faces would have correspondingly higher MOE and MOR properties. Surprisingly, the steam-injected boards had slightly higher average bending properties than the control boards. This phenomenon could be the result of less flake damage sustained by the steamed boards or may be an indication of an improvement in bonding characteristics.

Face strength, however, is deteriorated by steaming. Tests on unsanded samples showed the deterioration to decrease as press closure rates became faster and steaming times prior to closure became shorter. Sanding to a depth of 0.020 in. (0.5 mm) improved the face strength of all boards except those made with a long (20-second) period of steaming prior to press closure. No differences in the face strengths of the bottom and top surfaces were observed.

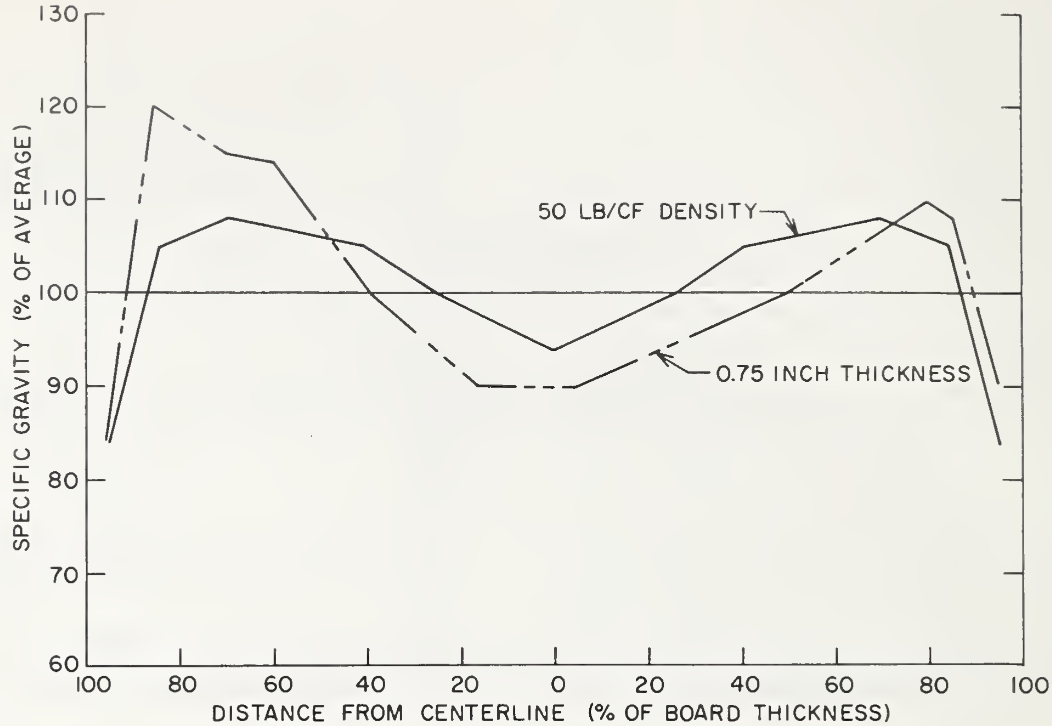

Figure 12. *Density profiles for 3/4 in. thick and 50 lb/ft³ density steam-injected boards.*

Dimensional Stability

Other researchers have reported large improvements in dimensional stability properties of boards steamed in a sealed chamber [2, 12]. No major improvements in the properties of thickness swell, linear expansion, and water absorption occurred when boards were subjected to steaming, as described herein. Conversely, no reduction of dimensional stability properties occurred in the minimum press-time boards. Usually boards having reduced IB, bending, and shear properties characteristic of the minimum time boards are also characterized by poorer dimensional stability properties.

Minimum Press Times

Since few thermal- or pressure-induced changes occur during early stages of closure, press time has been defined in this study as beginning when the mat has been compressed to a density of 20 lb/ft³ (320 kg/m³), or at the time steam is first injected [if this occurs prior to reaching 20 lb/ft³ (320 kg/m³)] and ending at the moment the press begins to open. This definition is preferred when comparing reduction in press times caused by rapid heat transfer, since it eliminates those variables associated with press-closure capabilities and material-bulk densities. The minimum time in which a ½ in. (13 mm), 40 lb/ft³ (641 kg/m³) phenolic-bonded board could be made was 90 seconds. Internal bonds of a 90-second board made with a steaming time of 8 seconds prior to closure and 20 seconds following closure were 102 lb/in.² (703 kPa). Interlaminar shear averaged 402 lb/in.² (2770 kPa). These values are comparable to the IB and IS properties averaged for the control boards.

Table 2. Physical properties[1/]

Board type No.	SG	IB	IS maximum load	Bending		Face strength		TS		LE	
				MOE	MOR	Unsanded[2/]	Sanded	90	VPS	90	VPS
		$lb/in.^2$	$lb/in.^2$	$klb/in.^2$	$lb/in.^2$	$lb/in.^2$	$lb/in.^2$	- - - - - % - - - - -			
GROUP 1--4-MINUTE PRESS TIME, STEAM INJECTED AT 0.320 SG											
0	0.657	123	426	603	4,420	135	142	13	21	0.21	0.24
1	0.655	128	449	640	4,650	125	108	12	17	0.20	0.23
2	0.650	110	372	578	4,160	117	121	15	20	0.20	0.24
3	0.634	113	431	622	4,450	95	122	10	23	0.20	0.26
19	0.651	130	448	636	4,850	125	159	8	17	0.18	0.22
4	0.692	123	433	587	4,200	70	90	10	25	0.21	0.28
Average	0.656	121	431	611	4,460	111	124	11	21	0.20	0.25
GROUP 2--4-MINUTE PRESS TIME, STEAM INJECTED AT 0.401 SG											
5	0.671	118	429	654	5,090	140	152	7	22	0.20	0.25
6	0.675	101	371	630	4,460	103	130	6	21	0.20	0.24
7	0.638	110	431	669	4,860	111	132	7	21	0.20	0.26
8	0.696	121	427	652	4,890	144	159	8	21	0.20	0.24
9	0.647	111	423	641	4,670	128	132	6	18	0.18	0.23
10	0.660	121	447	604	4,690	96	139	7	20	0.20	0.24
11	0.640	120	450	609	4,510	99	139	7	18	0.20	0.27
Average	0.661	114	425	637	4,740	117	140	7	20	0.20	0.25

Table 2. Physical properties[1/]--con.

Board type No.	SG	IB	IS maximum load	Bending		Face strength		TS		LE	
				MOE	MOR	Unsanded[2/]	Sanded	90	VPS	90	VPS
		$lb/in.^2$	$lb/in.^2$	$klb/in.^2$	$lb/in.^2$	$lb/in.^2$	$lb/in.^2$	- - - - -	%	- - - - -	
GROUP 3--2-MINUTE PRESS TIME, CLOSING RATE 15 in./min											
14	0.620	44	160	529	3,210	143	152	9	21	0.23	0.34
15	0.694	106	410	629	4,400	134	162	6	18	0.22	0.26
16	0.675	106	355	677	4,640	142	171	7	16	0.23	0.26
17	0.655	91	329	667	4,400	170	147	6	21	0.21	0.27
18	0.680	110	383	638	4,500	120	185	7	16	0.21	0.27
Average[3/]	0.676	103	369	653	4,480	142	166	7	18	0.19	0.24
GROUP 4--BOARD DENSITY AND THICKNESS VARIATIONS											
12 (50 lb/ft^3)	0.825	125	475	772	5,430	127	142	6	25	0.19	0.30
13 (0.75 in.)	0.675	105	390	573	4,140	101	129	6	19	0.17	0.21
GROUP 5--MINIMUM PRESS TIMES											
20	0.655	102	402	603	3,930	123	110	6	19	0.22	0.30
21	0.646	71	250	617	4,050	161	171	8	20	0.23	0.27
22	0.649	65	308	593	3,990	134	132	9	22	0.23	0.27
23	0.650	40	234	503	3,030	146	146	10	21	0.26	0.33
25	0.646	37	234	500	2,690	119	128	10	22	0.24	0.30

Table 2.--Physical properties[1/]--con.

Board type No.	SG	IB	IS maximum load	Bending		Face strength		TS		LE	
				MOE	MOR	Unsanded[2/]	Sanded	90	VPS	90	VPS
		$lb/in.^2$	$lb/in.^2$	$klb/in.^2$	$lb/in.^2$	$lb/in.^2$	$lb/in.^2$	- - - - -	-	%	- - - - -
GROUP 6--CONTROLS (NO STEAM INJECTION)											
31	0.643	112	420	625	4,400	165	159	8	21	0.20	0.22
26	0.681	112	454	669	4,400	165	153	13	22	0.19	0.17
27	0.618	106	357	564	4,160	149	180	11	19	0.21	0.21
28	0.658	117	403	653	4,420	178	165	15	21	0.21	0.20
68	--	[4/]78	--	558	3,840	--	--	--	--	--	--
Average[5/]		112	408	628	4,345	164	164	12	23	0.20	0.20
29 (50 lb/ft^3)	0.816	129	499	805	5,930	175	175	14	23	0.21	0.22
30 (0.75·in.)	0.653	116	354	696	4,780	170	186	11	21	0.22	0.16

1/ SG = specific gravity, IB = internal bond, IS = interlaminar shear, MOE = modulus of elasticity, MOR = modulus of rupture, TS = thickness swell, LE = linear expansion. Figures are average of two boards except for board types 20, 25, 31, 67--one board, and 23 and 28--three boards; from each board 4 IB, 2 IS, 4 MOE, 4 MOR, 4 TS, 4 LE, 4 face strength (sanded top surface), 4 face strength (unsanded top surface), 4 face strength (unsanded bottom surface) samples were tested (Fig. 5). SG is from density gradient sample.

2/ Average of top and bottom surfaces.

3/ Average does not include board type 14.

4/ Two of four samples delaminated.

5/ Average does not include board type 68.

Doubling the rate of closure and decreasing the steam time prior to closure to 4 seconds resulted in a reduction in IB properties to 71 lb/in.^{2} (490 kPa) and IS properties to 250 lb/in.^{2} (1723 kPa). Reductions of press times below 90 seconds caused successively larger reductions in physical properties. Most of the minimum press-time boards were made using a 4-second period of steaming prior to closure and an 18- to 25-second period of steaming following closure. Additional work exploring variables in steam times and press closure rates indicates that the phenolic resin used in this study as well as other similar resins required a minimum of 90 seconds of cure time in order to achieve good board properties.

Similar cure times were found necessary when pressing in a conventional fashion. Core temperatures in a conventionally pressed board reached 220°F in 1.5 to 2 minutes. Conventional boards made in 2.5 minutes delaminated. When press time was increased to 3 minutes, the boards had marginal properties. Control boards made in 4 minutes and in 10 minutes had similar properties.

CONCLUSION

Extensive exploratory research has shown that saturated steam injected into a flakeboard mat substantially reduces press times by causing a rapid transfer of heat to the core. Injection of steam prior to compressing the mat to a critical density of 27 lb/ft^3 (432 kg/m^3) and penetration of this steam to the core prior to reaching a density level of 35 lb/ft^3 (561 kg/m^3) open permanent steam passages that prevent condensation problems and eliminate the need for a sealing ring.

This study showed that because of the rapid heat transfer from the faces to the core of the board, minimum press times of steam-injected boards are essentially a function of resin-curing rate. For the phenolic resins reported in this study, curing time was found to be approximately 90 seconds.

The study also showed that injection of steam into a mat partially plasticizes the furnish, thereby reducing the closing pressure to approximately 40% of that needed in conventional pressing.

Also, very flexible control over the vertical density profile is obtained through proper choices of steam initiation, duration of steaming, and press closure rate.

Finally, the low-density face characteristic of a steam-pressed board can be eliminated in a normal sanding operation, and resultant board properties are comparable to those found in conventional hot-pressed boards.

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